Short Paper
A Short Subtitle

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Abstract

This is the abstract. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Vestibulum augue turpis, dictum non malesuada a, volutpat eget velit. Nam placerat turpis purus, eu tristique ex tincidunt et. Mauris sed augue eget turpis ultrices tincidunt. Sed et mi in leo porta egestas. Aliquam non laoreet velit. Nunc quis ex vitae eros aliquet auctor nec ac libero. Duis laoreet sapien eu mi luctus, in bibendum leo molestie. Sed hendrerit diam diam, ac dapibus nisl volutpat vitae. Aliquam bibendum varius libero, eu efficitur justo rutrum at. Sed at tempus elit.

Keywords: Index Insurance, Moral Hazard, Fisheries, Conservation

1. Moral Hazard Induced Behavior Change in Fisheries Index Insurance

Fishing is a risky business. Environmental fluctuations directly impact fishers of all scales from large industrial vessels to small scale subsistence fishers. Fishing is a vital economic engine to coastal communities and is the primary source of protein for millions of people[?] [?] [?] . Supporting these communities requires protection from enormous degrees of environmental risk.

Environmental variability in factors such as sea surface temperature or wind speeds impact fishery biological and economic productivity. Marine heatwaves increase animal thermal stress diminishing reproductive ability[?] , stunting growth[?] , pushing species outside their usual habitats[?] , and may directly increase mortality[?] . Expanding fish habitat ranges increase costs when moving beyond the fishing grounds of established ports[?] . The variability from marine heatwaves alone impacts 77% of species within economic exclusion zones and reduce maximum catch potential by 6%[?] . Marine heatwaves are often accompanied by harmful algal blooms and diseases leading to additional fishery collapses[?] .

The devastation of marine heatwaves was made clear in October 2022 when the Alaskan snow crab fishery was shut down after an assessment revealed an 87% decline in population from 2018[?] . New evidence suggests that the marine heatwave increased caloric demands while tightening the snow crab range leading to a mass starvation event[?] . The fishery provided $132 million from landings and $174 million from processing in 2020, and the impacts will reverberate throughout the community[?] . Recorded marine heatwaves have become more frequent[?] and climate change may continue to increase heatwave frequency as climate distributions become more variable[?] .

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Weather can also impact fisher harvesting efficiency beyond influencing the health of the underlying stock. This influence is more salient in fisheries than agriculture. Rolling seas and high wind speeds make it more difficult to harvest[?] in addition to raising the danger to crew and vessel[?]. All together, environmental shocks increase total income variability by changing harvest productivity or costs.

Individual choices by fishers and fishery management mitigate environmental risk. However, there is a lack of financial tools available to fishers to address income risk as a result of environmental fluctuations[?,?]. In the United States, financial relief currently comes from government issued disaster payments to afflicted fishery communities[?]. Since 1990, the United States has issued nearly $2 billion dollars to fishing communities after a disaster was declared. Environmental disasters, such as hurricanes, marine heatwaves, and harmful algal blooms, were solely responsible for 56% of the payments and partially responsible for another 27%. This system may be ineffective as there is an average of 2 years between disaster impact and fund relief[?], and may inequitably distribute funds[?]. New financial tools need to be developed to alleviate financial and income risk for coastal communities[?,?].

Insurance may be an ideal financial tool for risk management in fisheries as it is scalable, protects against environmental shocks, and smooths income for fishers. Currently, insurance in fisheries is primarily used to protect assets such as vessel hulls or fishing gear[?]. Insurance coverage could be expanded to include income variability. Weather fluctuations impact fisher income and their livelihoods. An insurance product covering environmental risk could improve fisher welfare and promote community resilience.

Policy makers have begun pushing for new fisheries insurance programs modeled after agricultural crop insurance programs[?]. One research study previously examined the suitability of crop insurance programs for Salmon fisheries in Bristol Bay, Alaska. Ultimately, the fishery was deemed not suitable for insurance due to exorbitant program costs, inability to quantify peril in a fishery setting, and a moral hazard disincentiving fishers to exit the fishery[?]. However, new innovative insurance products and greater fishing data availability have reduced barriers for fisheries insurance reinvigorating investigations into the viability of new products.

Index insurance is one such product touted by practitioners as a prime candidate for fisheries productivity insurance. Index insurance gained traction in agriculture as an effective alternative to traditional crop insurance in developing countries because it had lower administrative cost, minimized moral hazards, and does not require claim verification[?,?]. Whereas crop insurance requires an assessment of loss to an individual farm, index insurance uses an independent measure as the basis for issuing payouts to all policyholders. For example, a pilot program through the Caribbean Oceans and Aqaculture Sustainability Facility (COAST) uses index insurance to payout a set amount to fishers when indices of wave height, wind speed, and storm surge indicate a hurricane[?]. Triggers are the index values that initiate a payout. Contract design revolve around establishing suitable triggers to cover environmental loss. Interest is growing in expanding index insurance to cover other environmental shocks to more fisheries.

Index insurance seems particularly well suited for fisheries because it does not require individuals' catch histories, which can be problematic even in the most well regulated fisheries. This allows index insurance to pay out much faster than traditional indemnity insurance. Policyholders can receive compensation as quickly as a day after a trigger is initiated and rarely have to wait longer than two weeks. Also, index insurance by design integrates correlated risks into its payout structures so that when one individual receives a payout others do as well.

One crucial area that remains unaddressed is the potential influence of insurance on fishers behavior. Moral hazards are decisions by insured agents that they would not otherwise take if they were uninsured[?]. Owning insurance contracts will change fisher harvesting decisions through moral hazards. Because fisheries are ecologically sensitive to changes in harvest due to their dynamic nature, care must be taken to prevent adverse incentives that increase fishing pressures. The proposed moral hazard in the Bristol Bay context is the decision that fishers would choose to stay in the fishery if they were insured from losses, when the fishers would otherwise have left the fishery with no insurance. The authors provided no theoretical nor empirical evidence to support their claim. However, moral hazards may not be completely detrimental from a conservation perspective. Instead, the insured agent's decision could reduce an environmentally damaging behavior because of the new incentive structure of the insurance[? ?]. Insurance will change the behavior surrounding fisher decisions that will impact any fishery. We provide the first theoretical application of index insurance on fisher behavior change in order to predict if index insurance will incentivize overfishing or conservation.

Agricultural economists have grappled with insurance moral hazards for decades. Key lessons can be imported into the fishery landscape to mold more accurate predictions of moral hazard impacts. One crucial insight originates from the notion of risk effects. Risk effects are the changes in production volatility from a change in an input[?]. Insurance interacts with risk effects by changing the perception of risk surrounding additional input use[?]. Through theoretical and empirical work in agriculture, it is known that insurance will increase risk increasing input use while decrease risk decreasing input use[? ? ?]. However, risk effects are an under explored phenomena in fisheries and the complexity of fishery production requires further examination.

This paper explores how fishers could change their behavior if offered viable index insurance contracts. Section 1.1 provides a literature review of moral hazards from insurance in agriculture. Section 1.2 builds a model to prove that index insurance in common pool settings can lead to conservation improvements depending on the risk effects of inputs. Section 1.3 expands the index insurance model to include multiple inputs crucial in fisheries production. Numerical results in Section 1.4 estimate potential biomass loss or recovery with an index insurance program. Implications for the suitability of fishery index insurance are discussed in Section 1.5. Fishery index insurance ultimately has ambiguous effects on conservation. Before widespread adoption, careful consideration must be given to how insurance will incentivize or disincentivize overfishing.

1.1. Input Risk

1.1.1. Risk effects in agriculture

Environmental moral hazards have been studied in indemnity crop insurance, and observed in index insurance policies. The interaction between risk and production inputs drives the impact insurance has on harvest. Production inputs in their broadest classification are the capital and labor inputs firms use to produce outputs. For farmers this includes the tractors, chemicals, and technology used to plant, grow, and harvest crops. Farmers expect a set amount of harvest at the end of the year using all combined inputs. However, nature through rain and temperature is the final input for growing corps. Weather is volatile and leads to random variation in harvest. Certain inputs farmers use, such as irrigation or frost covers, can change volatility in harvest due to weather. The changes in volatility from a change in an input are called "risk effects"[?]. If the variance of production increases with more of an input it is risk-increasing. Likewise, inputs that lower production variance are risk-decreasing.

After implementation of US federal crop insurance in the 1980s, agricultural economists became interested in how moral hazards would impact both the provision of insurance and the effect on farm production. Moral hazards can be broken down into two components. The first is "chasing the trigger" where policyholders intentionally conduct actions that lead to higher probabilities of payouts. Farmers purposely lowering crop yields to get a payout illustrates "chasing the trigger". This is the moral hazard most insurance companies seek to reduce and index insurance completely eliminates through use of an independent-verifiable index. The second component is "risk reduction". Possessing an insurance contract protects policyholders from risk. Policyholders may reoptimize their decisions once protected from risk. Risk effects play a dramatic role in moral hazard behavior changes through "risk reduction".

? presented a theoretical model to investigate how insurance interacts with risk effects and leads to changes in optimal inputs. He found that insurance always reduces risk decreasing input use, while insurance will lead to greater risk increasing input use if the variance elasticity of production is less than the mean elasticity of production. His work was under an indemnity insurance framework hence why there is a tension on risk increasing inputs. Insurance protection from smaller variance changes outweigh the ability to "chase the trigger" to elicit payouts. In an index insurance setting, this tension evaporates given the inability to change the probability of payouts so that insurance always lead to greater risk increasing input use[?] .

Empirical studies further solidified the importance of insurance on risk increasing and risk decreasing input use. However, the direction for specific inputs remains ambiguous. **?** showed farmers with insurance use more fertilizers than farmers without insurance. **?** aggregated fertilizer and pesticide use as total chemical input and found insurance lowered input use. **?** added theoretical and experimental evidence that insurance impacts application of fertilizers. They focused more on the conditional distributions of yield as a function of input use. Then they used experimental farms at Iowa State to show that fertilizer use decreases the probability of low yields and acts as a risk-decreasing input. They simulate their results on US crop insurance to indicate how much insurance lowers fertilizer use. Recently, **?** used multiple identification strategies to show insurance has no effect on pesticide use for a variety of crops in the United States. They argue the inherent endogeneity of the decision to insure and apply pesticide makes answering this question a near impossible challenge.

? were the first to connect the potential of insurance reducing fertilizer use for environmental benefits. Accounting for environmental conditions of the field, such as soil erosion and surface runoff, insurance leads to significantly lower fertilizer use, but no change in pesticide use. The authors did not extrapolate further in connecting fertilizer runoff reductions to surrounding fields or the environment as a whole. **?** expanded the impacts of insurance on environmental quality to include extensive decisions such as crop selection and acreage. Overall, insurance leads to statistically significant changes in pollution levels, but are proportionally rather small drivers of agricultural pollution[?] .

Insurance changes input use beyond chemical application. **?** use the 1994 Farm Bill as an instrument to show groundwater use increased with greater insurance coverage. The authors suggest the transition to more water intense crops such as cotton was the primary driver. Thus, extensive input decisions change with insurance decisions. Other studies have identified small but significant changes in total acreage as a result of insurance coverage[?, ?] .

Empirically, index insurance stimulates changes in farm production in developing countries. Though the effects on intensive and extensive inputs remains similar, the interpretation can be quite different. Agricultural index insurance is primarily used in developing countries to reach small-scale farmers as opposed to capital rich industrial farms where indemnity insurance is prevalent. For example, increasing capital and chemical investments in developing countries agriculture is a key development goal. Index insurance stimulated investment in inputs and other agricultural capital in Kenyan maize, Burkina Faso cotton, and Mali cotton farmers[?, ?, ?] . Index insurance also encouraged farmers in India to plant higher yield, but riskier crops[?] .

Increased investments can also harm communities, particularly in common pool resources such as livestock grazing. Kenyan index insurance for livestock discentivized preemptively selling animals after negative shocks, leading to larger herds in aggregate[?] . Though no empirical work has been done on the long term effects, two theoretical studies suggest insurance increases the stocking levels of grazing animals in pastures. Higher stocking densities diminish the pastures long-term health reducing overall utility gains of insurance[?, ?] . Caution must be demonstrated when dealing with complex bio-economic systems, otherwise maladaptive outcomes can lead to greater harm[?] .

However, both theoretical studies implicitly assume that stocking is a risk increasing variable. The structure of their production functions may be valid in their settings, but their results are be driven by the unidirectional nature of the risk effects. This begs the question, do changes in input use through index insurance still hold in common pool resources?

The race to fish mentality that leads to overexploitation is a defining characteristic of fisheries. If index insurance always leads to increased input use in common pool resources, then implementing index insurance in fisheries will lead to maladaptive outcomes.

1.2. *Index insurance in common-pool resources*

Fisheries are highly dynamic systems because of year to year variation in biological growth and reproduction stemming from environmental variables. Overfishing impacts are exacerbated through ecological dynamics as lower fish abundances carry over to the next year. With 35.6% of global fisheries overfished and 57.3% at maximum sustainable yield**?** , ensuring new index insurance programs do not push more fisheries toward overfishing is a crucial first assessment.

Input changes in fisheries lead to more harvest and pressure on the biological system. Common pool settings remain prevalent in fisheries management. Entry limits through vessel or permits are popular strategies to limit access to fishing resources. Small scale cooperative management can exclude non-community participants, but are still common pool resources. Therefore it is valuable to examine fisheries index insurance in a common pool setting before tying in additional complexities such as management.

1.2.1. *Model*

Environmental stochasticity can translate to fluctuations in the biological component of fishery models. Biomass abundance is a key input for density dependent harvest functions in addition to harvesting technology. To start, we will first examine fishing technology that is aggregated into a single effort variable to determine how overall harvest decisions may change with insurance for risk averse fishers. An example of harvest production function by individual fishers is given by Equation 1.

$$\begin{aligned} y_i &= q\tilde{B}e_i^{\alpha} \\ \tilde{B} &\sim N(\hat{B}, \sigma_b^2) \end{aligned} \tag{1}$$

Where q is a catchability coefficient, $\tilde{B}$ is the random abundance of fish with a mean at $\hat{B}$ and a variance σ_b^2, and effort for fisher i is e_i. We can break apart the random variable into a mean effect $(\hat{\beta})$ and variance component (ω).

$$\begin{aligned} \tilde{B} &= \hat{B} + \omega \\ \omega &\sim N(0, \sigma_b^2) \end{aligned} \tag{2}$$

Adding Equation 2 back into Equation 1 leads to:

$$y_i = qe_i^{\alpha}(\hat{B} + \omega) \tag{3}$$

This formulation is comparable to many standard fishery models. Randomness could originate from weather shocks impacting equilibrium biomass in the current period or measurement error surrounding a stock. For example Equation 3 is identical to **?** production function when $\alpha = 1$. This specification is still inherently risk increasing. Instead, we could allow for flexible risk effects. **?** separate input effects into mean and risk components. We can do the same for fishery production where effort controls mean harvest and harvest variance.

$$y_i = qe_i^{\alpha}\hat{B} + \omega q e^{\beta} \tag{4}$$

Risk effects are controlled by β. Biomass is an input into the fishers production function so that greater biomass leads to greater production. We can generalize the production function with mean effects $f(e_i)$ and risk effects $h(e_i)$.

$$y_i = \hat{B}f(e_i) + \omega h(e_i) \tag{5}$$

Mean production functions $f(e_i)$ are concave with increasing diminishing returns $(f'(e_i) > 0, f''(e_i) < 0)$ while risk effects may exhibit risk increasing properties $(h'(e_i) > 0)$ or risk decreasing properties $(h'(e_i < 0))$.

Fish biomass is dynamic and depends on environmental and biological variables. Equilibrium biomass is the level of fish stock that balances growth with aggregate harvest. All fishers harvest from the equilibrium biomass in a common pool setting. Equilibrium biomass ought to remain constant for a set limited number of fishers and initial starting conditions. There could be random shocks surrounding the equilibrium biomass captured by the ω term. The biology of the system is independent of fisher actions. Therefore, fishers can only affect equilibrium biomass through their own harvest e_i and everyone else's harvest $e_{\sim j}$. Equilibrium biomass is a function of aggregate efforts.

$$y_i = \hat{B}(e_i, e_{\sim j})f(e_i) + \omega h(e_i) \tag{6}$$

Fishers derive utility from profits. Adding a cost function that is equivalent for each fisher yields a profit function.

$$\pi_i = \hat{B}(e_i, e_{\sim j})f(e_i) + \omega h(e_i) - c(e_i) \tag{7}$$

To most seamlessly integrate index insurance, we can break situations into a bad state of the world that occurs with probability p and a good state of the world that happens with probability $(1-p)$. We can use ω to create an index to indemnify payouts because it captures the randomness of fishers profits. In reality, the index would be a weather variable known to impact biomass such as sea surface temperature, and the trigger are critical thresholds that cause weather to deviate from equilibrium biomass. Here, all stochasticity is captured by ω. We can align the states of the world to a shock trigger $\bar{\omega}$ so that $p = P(\omega < \bar{\omega})$ and $1 - p = P(\omega > \bar{\omega})$.

Insurance then pays a constant amount γ in the bad state. Actuarilly fair insurance allows the premium paid in both states to be the probability of receiving a payout $p\gamma$. Additionally, if we set the trigger to $\bar{\omega} = 0$ to indicate any time weather negatively impacts production, we can then separate out profit into good and bad states as well with $\omega_g > 0$ and $\omega_b < 0$ entering into Equation 7. Fishers are risk averse with a concave utility function $u'(\pi_i(e_i), \gamma) > 0$ and $u''(\pi_i(e_i), \gamma) < 0$. Putting it all together, fishers will maximize expected utility by selecting their own individual effort e_i while accounting for the changes in equilibrium biomass due to other fishers choice of effort.

$$F \equiv \max_{e_i} \mathbb{E}[u] = pu(\pi_b + (1-p)\gamma) + (1-p)u(\pi_g - p\gamma) \tag{8}$$

The first order condition that solve Equation 8 is then:

$$\frac{\partial F}{\partial e_i} = pu'(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial e_i} + (1-p)u'(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial e_i} = 0 \tag{9}$$

For notional ease, the inputs of the profit function are dropped, but as shown in Equation 7 profit in both states (π_b=bad, π_g=good) remains a function of effort, equilibrium biomass, and weather shocks.

To find the impact of insurance on optimal effort we can apply Cramer's Rule to the first order conditions.

$$\frac{\partial e_i^*}{\partial \gamma} = -\frac{\frac{\partial F}{\partial e_i \partial \gamma}}{\frac{\partial^2 F}{\partial e_i^2}}$$

By definition of a maximization problem, $\frac{\partial^2 F}{\partial e_i^2}$ is negative so we can focus solely on the numerator to sign the impact of insurance on optimal individual effort. Then we'll use the change in individual effort to understand the implications on conservation.

Proposition 1.1. *Index insurance will raise (lower) individual fisher effort when effort is risk increasing (decreasing)*

Proof. Differentiate equation Equation 9 with respect to insurance.

$$\frac{\partial F}{\partial e_i \partial \gamma} = (1-p)u''(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial e_i}(-p) + pu''(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial e_i}(1-p) \tag{10}$$

Suppose insurance fully covers the loss between states, then utility in the good state and bad state are equal to each other so that we can factor out like terms in Equation 10.

$$\frac{\partial F}{\partial e_i \partial \gamma} = (1-p)pu''(\cdot)[\frac{\partial \pi_b}{\partial e_i} - \frac{\partial \pi_g}{\partial e_i}] \tag{11}$$

The first term outside the brackets is negative by the definition of concave utility. Marginal profits across states share the same mean productions and costs as effort decisions must be made before the realization of the states. Subbing those terms in to Equation 11 demonstrates how they cancel out allowing us to sign the interior brackets.

$$\begin{aligned}\frac{\partial \pi_b}{\partial e_i} - \frac{\partial \pi_g}{\partial e_i} &= \omega_b h'_{e_i}(e_i) + \cancel{f'_{e_i}(e_i)\hat{B}_{e_i}(e_i, e_{\sim j})} + \cancel{[\frac{\partial \hat{B}}{\partial e_i} + \frac{\partial \hat{B}}{\partial e_{\sim j}}\frac{\partial e_{\sim j}}{\partial e_i}]}f(e_i) - \cancel{c'_{e_i}(e_i)} \\ &\quad - \omega_g h'_{e_i}(e_i) - \cancel{f'_{e_i}(e_i)\hat{B}_{e_i}(e_i, e_{\sim j})} - \cancel{[\frac{\partial \hat{B}}{\partial e_i} + \frac{\partial \hat{B}}{\partial e_{\sim j}}\frac{\partial e_{\sim j}}{\partial e_i}]}f(e_i) + \cancel{c'_{e_i}(e_i)} \\ &= \omega_b h'(e_i) - \omega_g h'(e_i)\end{aligned} \tag{12}$$

If an input is risk increasing then $h'(e_i) > 0$ with $\omega_b < 0$ and $\omega_g > 0$. Then Equation 12 is negative.

$$\frac{\partial \pi_b}{\partial e_i} - \frac{\partial \pi_g}{\partial e_i} = \overbrace{\omega_b h'(e_i) - \omega_g h'(e_i)}^{-}$$

Now can completely sign Equation 11 by subbing in the bracket sign when effort is risk increasing.

$$\frac{\partial F}{\partial e_i \partial \gamma} = \overbrace{\overbrace{(1-p)pu''(\cdot)}^{-}[\overbrace{\frac{\partial \pi_b}{\partial e_i} - \frac{\partial \pi_g}{\partial e_i}}^{-}]}^{+} \tag{13}$$

Therefore, Equation 13, index insurance will raise individual fisher effort when effort is risk increasing.

Risk decreasing inputs have $h'(e_i) < 0$ by definition. Subbing this into Equation 12 shows the interior bracket is positive and thus insurance lowers optimal individual effort when effort is risk decreasing.[1]

$$\frac{\partial \pi_b}{\partial e_i} - \frac{\partial \pi_g}{\partial e_i} = \overbrace{\omega_b h'(e_i) - \omega_g h'(e_i)}^{+}$$

[1] Intuitively, if inputs are risk decreasing, then marginal profits in the bad state should be higher as the risk reducing effects lower the negative impact of the shock. In the bad state it would be beneficial to invest more effort to reduce the exposure to risk.

$$\frac{\partial F}{\partial e_i \partial \gamma} = \overbrace{\overbrace{(1-p)pu''(\cdot)}^{-}\overbrace{[\frac{\partial \pi_b}{\partial e_i} - \frac{\partial \pi_g}{\partial e_i}]}^{+}}^{-} \tag{14}$$

When effort possess no risk effects Equation 12 is zero and there is no change in optimal effort with insurance.

□

Proposition 1.1 solidifies the direction insurance impacts on risk effects still hold in a classic common pool resource. Imposing a Nash Equilibrium on the fishery will elucidate potential conservation impacts insurance may have on a fishery.

Proposition 1.2. *In a symmetric Nash equilibrium with limited entry, index insurance will lower (raise) equilibrium biomass when effort is risk increasing (decreasing)*

Proof. First take the total derivative of equilibrium biomass.

$$\frac{d\hat{B}}{de_i} = \frac{\partial \hat{B}}{\partial e_i} + \frac{\partial \hat{B}}{\partial e_{\sim j}} \frac{\partial e_{\sim j}}{\partial e_i} \tag{15}$$

Symmetric Nash equilibrium imply that $e_i = e_{\sim j}$. Subbing into the total derivative simplifies the expression for every n fishers.

$$\begin{aligned} \frac{d\hat{B}}{de_i} &= \frac{\partial \hat{B}}{\partial e_i} + (n-1)\frac{\partial \hat{B}}{\partial e_i}\frac{\partial e_i}{\partial e_i} \\ &= n\frac{\partial \hat{B}}{\partial e_i} \end{aligned}$$

By definition $\frac{\partial \hat{B}}{\partial e_i} < 0$ with increasing e_i as more harvest effort lowers biomass. Applying Proposition 1.1 we know that e_i raises with index insurance when $h'(e_i) > 0$ and thus equilibrium biomass decreases. Insurance lowers risk reducing effort so that equilibrium biomass $\hat{B}$ increases.

□

Bioeconomic equilibriums arise when aggregate harvest exactly equals stock growth. Applying a logistic growth function into a fishery shows the implications of Proposition 1.2 quite clearly.

```
library(tidyverse)
```

```
Warning: package 'ggplot2' was built under R version 4.3.2
```

```
Warning: package 'dplyr' was built under R version 4.3.2
```

```
Warning: package 'stringr' was built under R version 4.3.2
```

```
-- Attaching core tidyverse packages ------------------------ tidyverse 2.0.0 --
v dplyr     1.1.4     v readr     2.1.4
v forcats   1.0.0     v stringr   1.5.1
v ggplot2   3.4.4     v tibble    3.2.1
v lubridate 1.9.3     v tidyr     1.3.0
v purrr     1.0.2
-- Conflicts ------------------------------------------ tidyverse_conflicts() --
x dplyr::filter() masks stats::filter()
x dplyr::lag()    masks stats::lag()
i Use the conflicted package (<http://conflicted.r-lib.org/>) to force all conflicts to become errors
```

```r
library(latex2exp)
b=seq(0,1000,1)
r=3
k=1000

h=r*b*(1-b/k)

a_low=.45
low_h=a_low*b
rr_low_h=(a_low-.1)*b
ri_low_h=(a_low+.1)*b

a_hi=2
hi_h=a_hi*b
rr_hi_h=(a_hi-.15)*b
ri_hi_h=(a_hi+.15)*b

lw=2

# intersection x breaks
b_low=k/r*(r-a_low)
b_low_rr=k/r*(r-(a_low-.1))
b_low_ri=k/r*(r-(a_low+.1))

b_hi=k/r*(r-a_hi)
b_hi_rr=k/r*(r-(a_hi-.15))
b_hi_ri=k/r*(r-(a_hi+.15))

# intersection y breaks

h_low=h[which.min(abs(b-b_low))]
h_low_rr=h[which.min(abs(b-b_low_rr))]
h_low_ri=h[which.min(abs(b-b_low_ri))]
h_hi=h[which.min(abs(b-b_hi))]
h_hi_rr=h[which.min(abs(b-b_hi_rr))]
h_hi_ri=h[which.min(abs(b-b_hi_ri))]

temp<-data.frame(b,rr_low_h,ri_low_h,rr_hi_h,ri_hi_h) |>
  pivot_longer(cols = -b,names_to = "type",values_to = "h") |>
```

```
  mutate(lt=ifelse(stringr::str_detect(type,"rr"),"Risk Decreasing",ifelse(stringr::str_detect(type


ggplot(data.frame(b,h),aes(x=b,y=h))+geom_line(linewidth=lw+1)+
  geom_path(data=temp,aes(x=b,y=h,linetype=lt,color=type),linewidth=lw)+
  geom_line(aes(x=b,y=low_h),color="black",linewidth=lw)+
  geom_line(aes(x=b,y=hi_h),linewidth=lw)+
  scale_x_continuous(breaks=c(b_hi_ri,b_hi,b_hi_rr,b_low_ri,b_low,b_low_rr,1000),labels=c(TeX(r'($\
  scale_y_continuous(breaks=c(h_hi_ri,h_hi,h_hi_rr,h_low_ri,h_low,h_low_rr),labels=c(TeX(r'($\hat{H
  labs(x="",y="")+
  scale_color_manual(values=c("black","black","black",'black','black','black'))+
  scale_linetype_manual(values=c("Neutral"="solid","Risk Increasing"="dotted","Risk Decreasing"="do
  theme_classic()+
  theme(legend.position=c(0.8,0.9))+
  guides(color="none",
         linetype=guide_legend(keywidth = 3,keyheight = 1))+
  labs(x="Equilibrium Biomass",y="Equilibrium Harvest")
```

```
Warning: Removed 1196 rows containing missing values (`geom_path()`).

Warning: Removed 600 rows containing missing values (`geom_line()`).
```

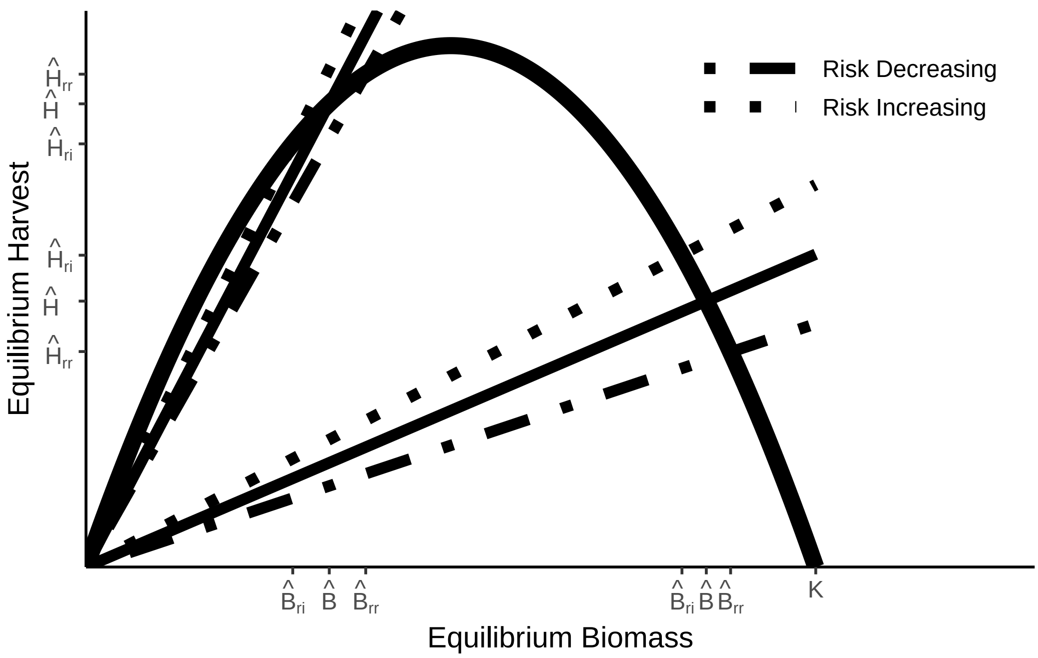

Figure 1: Equilibrium harvest and biomass levels change with index insurance depending on the risk effects of inputs. Deviations from initial harvest allocations (solid line) have different impacts at levels above and below maximum sustainable yield. Risk decreasing inputs (long dashes) will always lead to higher equilibrium biomass. Risk increasing inputs (short dashes) will always lead to lower equilibrium biomass.

Index insurance can lead to conservation benefits in common pool resources if the production inputs are risk decreasing, but the implications for harvest depend on the initial bioeconomic equilibrium. In Figure 1, the first initial bieconomic equilibrium to the left demonstrates overexploitation with biomass below maximum sustainable yield. A decrease an effort from index insurance stimulates faster growth of the stock allowing for more harvest in the future. Therefore fishers will be more protected from shocks with insurance, benefit from more current harvest, and there will be a a healthier stock of fish. Alternatively, if inputs are risk increasing, then index insurance will shift production to the right lowering harvest and biomass of the fish pushing the fishery further into overexploitation.

The second initial equilibrium to the right in Figure 1 is underexploited with biomass above maximum sustainable yield. The impact of index insurance on equilibrium biomass remains the same as when overexploited by Proposition 1.2, but the direction of harvest changes. Now, insurance will lower harvest for risk decreasing inputs and raise harvest for risk increasing inputs.

Proposition 1.2 offers policymakers a powerful tool to assess the viability of using index insurance to protect fisheries from overharvesting and provide conservation benefits. Conservation of common pool resources through insurance hinges on the risk effects of production technology. If policymakers are solely interested in conservation, then only knowing the direction of the fishery risk effects is necessary. In that case, only fisheries with risk decreasing inputs should be targeted for index insurance policies. Index insurance could also be used to incentivize fishing in low capacity communities, much like how index insurance is used in developing countries to stimulate agriculture investment. Since most fisheries are overfished, it is unlikely that a policymaker would target fisheries with risk increasing inputs with insurance to expand capacity and place more pressure on the fish stock.

Risk effects remain an elusive concept in fisheries. It is unclear how to preemptively identify fishery risk effects. Current bioeconomic models used to study fisheries do not account for risk effects. They are biased towards risk increasing inputs and therefore will always predict a lower equilibrium biomass.

Fishery bioeconomic models need to balance complexity in both the biological and economic systems. More emphasis as been placed on biological complexity with ecosystem-based management rising in prevalence. Though some models use Cobb-Douglas and other more flexible economic production models for harvest, most use a variation of the Gordon-Schaefer production model. The ability to create a proxy for stock abundance through catch per unit effort (CPUE), and its simplicity is why Gordon-Schaefer remains a useful modelling framework for fisheries. However, Gordon-Schaefer does not allow for flexible risk effects.

Proposition 1.3. *Gordon-Schaefer fishery production models with linear harvest and multiplicative shocks are always risk increasing.*

Proof. Risk effects can also be defined as the cross partial of the production function with respect to input and shock. If positive then an input is risk increasing, and if negative an input is risk decreasing.

$$\begin{aligned} y &= qeB\omega \\ \frac{\partial y}{\partial e \partial \omega} &= qB \\ &> 0 \end{aligned}$$

□

Fishery harvest (y) is a linear function of effort (e), stock abundance (B), and a catchability coefficient (q) acting as a measure of technological efficiency. Stock abundance and technological efficiency are always greater than zero. Without loss of generality, more sophisticated models will find similar limitations as they are extensions of the presented simple form. Cobb-Douglas are known to posses bias towards risk increasing inputs[?] , and age-structure models typically use the same linear profit as a Gordon-Schaefer at each age class with multiplicative environmental shocks[?] . Fox and Pella-Tomlinson models are more flexible production models, but each can reduce down to a Gordon-Schaefer through parameter choice.

Adding insurance to standard bioeconomic fishery models always leads to an increase in input use by Proposition 1.1, and a decrease in equilibrium biomass through Proposition 1.2. However, these models were often not designed to account for risk and risk preferences. Fishers are highly responsive to risk. They mitigate risk through a variety of measures. Fishers will choose consistent, known fishing grounds over risking exploring unknown spots**?** . Fishers choose to fish less after storms and hurricanes when financial risk is alleviated by transitioning to catch share programs**? ?** . In this context, effort can be seen as an *income* risk reducing input. If the variability of catch is reduced, then the pressure to fish to ensure consistent catch is also reduced.

To date, only one study has quantified risk effects in a fishery setting. **?** used data from four Norwegian fishing fleets to measure three input responses to risk. Each fishery possessed unique mixes of both risk increasing and decreasing inputs. For example, labor was found to be a risk decreasing input across all four groups, but only statistically significant in both pelagic seiners. Capital was risk increasing for coastal seiners and trawlers, but flipped to risk decreasing for purse seiners and trawlers. Fuel had a lower, but statistically significant positive risk increasing measure for three of the four groups.

However, total output variance fluctuated in ways where it was not clear what the total effect would be. Coastal seiners had significant risk decreasing effects in labor, but also significant risk increasing effects in fuel. Overall output variance was insignificantly different than zero. So while individual inputs impacted risk, overall impacts were unclear. Index insurance may raise or lower individual inputs depending on their own unique risk effects, but the overall direction of conservation cannot be determined. In order to apply the insights gained from index insurance in a common pool setting to the real world effects of Asche et al., (2020), our model must be expanded to understand how index insurance interacts with multiple inputs.

1.3. Insurance with multiple inputs

We can use the overarching framework from the previous section and expand it by adding multiple inputs. To simplify matters, we will focus on only one fisher, their choice of inputs and insurance, and a set biomass normalized to one.

Some inputs have varying risk effects. Interaction between inputs risk effects could change overall impacts from insurance to aggregate harvest and biomass. Fishers can use a vector of inputs X. Expected mean production $(f(X))$ and variance of outputs $(h(X))$ remains the same. We will use only two inputs, capital and labor, in our model. Total production thus equals:

$$y(k,l) = f(k,l) + \omega h(k,l)$$
$$\text{where } \omega \sim N(0,\sigma^2)$$

As before, random shocks that could be weather or biological shocks is captured by ω. Mean production possess classic production concavity so that $f'(k,l) > 0$ and $f''(k,l) < 0$. Flexible risk effects imply that $h'(k,l) \lesseqgtr 0$ so that risk increasing $h'(k,l) > 0$, risk decreasing $(h'(k,l) < 0)$, and no risk effects $h'(k,l) = 0$. The original specification of Just and Pope make no assumption on the form of the second derivative of the risk effect function. To assist signing later on further justification is required. The marginal impact of adding an input to production variance should have diminishing effects, because it is impossible to completely eliminate risk or experience infinite risks. Therefore, when $h'(k,l) > 0 \rightarrow h''(k,l) < 0$, and when $h'(k,l) < 0 \rightarrow h''(k,l) > 0$. The cross partial of risk effects on production $\frac{\partial h}{\partial k \partial l}$ must also be flexible and depend on how inputs interact with each other. For example, if adding an input does not contribute to the marginal variance of another input then $\frac{\partial h}{\partial k \partial l} = 0$. Inputs interactions could be complementary in that adding a risk decreasing input further enhances the risk reducing properties of the other inputs, e.g. $(\frac{\partial h}{\partial k \partial l} > 0)$. In other instances the inputs may interact counter actively in that adding more of a risk increasing input might reduce the effect of a risk decreasing input $\frac{\partial h}{\partial k \partial l} < 0$. In principle, when inputs share direction of risk effects, their cross partial ought to be complementary, and otherwise they will be counter productive.

Costs are convex, $c'(k,l) > 0$ and $c''(k,l) > 0$, in each input. Prices are constant and set at one so that production and costs together form random profits.

$$\pi(k,l) = f(k,l) + \omega h(k,l) - c(k,l) \tag{16}$$

We use the same insurance design from the previous section where payouts, γ, are triggered by $\omega < 0$, and we can partition profit into good states and bad states. Fishers now maximize expected utility by selecting both inputs, capital and labor.

$$F \equiv \max_{k,l} \mathbb{E}[u] = pu(\pi_b(k,l) + (1-p)\gamma) + (1-p)u(\pi_g(k,l) - p\gamma)$$

Taking the first order conditions yields:

$$\begin{aligned} \frac{\partial F}{\partial k} &= (1-p)u'(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial k} + pu'(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial k} = 0 \\ \frac{\partial F}{\partial l} &= (1-p)u'(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial l} + pu'(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial l} = 0 \end{aligned} \tag{17}$$

Given the existence of the first order condition, we can use the implicit function theorem (IFT) to look at the impact of an exogenous variable change locally at the solution. In other words, using IFT will clarify how a change to the insurance parameter γ will lead to new allocations of captial and labor. We can differentiate Equation 17 with respect to γ by the chain rule. This yields:

$$\begin{pmatrix} \frac{\partial F}{\partial k \partial k} & \frac{\partial F}{\partial k \partial l} \\ \frac{\partial F}{\partial l \partial k} & \frac{\partial F}{\partial l \partial l} \end{pmatrix} \begin{pmatrix} \frac{\partial k^*}{\partial \gamma} \\ \frac{\partial l^*}{\partial \gamma} \end{pmatrix} = - \begin{pmatrix} \frac{\partial F}{\partial k \partial \gamma} \\ \frac{\partial F}{\partial l \partial \gamma} \end{pmatrix}$$

Inverting the Hessian matrix to the other side allows us to isolate the effects on the optimal allocations.

$$\begin{pmatrix} \frac{\partial k^*}{\partial \gamma} \\ \frac{\partial l^*}{\partial \gamma} \end{pmatrix} = - \begin{pmatrix} \frac{\partial F}{\partial k \partial k} & \frac{\partial F}{\partial k \partial l} \\ \frac{\partial F}{\partial l \partial k} & \frac{\partial F}{\partial l \partial l} \end{pmatrix}^{-1} \begin{pmatrix} \frac{\partial F}{\partial k \partial \gamma} \\ \frac{\partial F}{\partial l \partial \gamma} \end{pmatrix} \tag{18}$$

Crammer's rule allows us to solve this system of equations so long as the determinant of the system is not equal to 0. Luckily, the determinant is a 2x2 hessian of a concave maximization problem. By definition it is strictly positive. Applying Crammer's rule to Equation 18 gives us:

$$\begin{pmatrix} \frac{\partial k^*}{\partial \gamma} \\ \frac{\partial l^*}{\partial \gamma} \end{pmatrix} = \frac{-1}{Det} \begin{pmatrix} \frac{\partial F}{\partial l \partial l} & \frac{-\partial F}{\partial k \partial l} \\ \frac{-\partial F}{\partial l \partial k} & \frac{\partial F}{\partial k \partial k} \end{pmatrix} \begin{pmatrix} \frac{\partial F}{\partial k \partial \gamma} \\ \frac{\partial F}{\partial l \partial \gamma} \end{pmatrix}$$

Solving the systems yields:

$$\begin{aligned} \frac{\partial k}{\partial \gamma} &= \frac{-1}{Det}\left[\frac{\partial F}{\partial l \partial l}\frac{\partial F}{\partial k \partial \gamma} - \frac{\partial F}{\partial k \partial l}\frac{\partial F}{\partial l \partial \gamma}\right] \\ \frac{\partial l}{\partial \gamma} &= \frac{-1}{Det}\left[\frac{-\partial F}{\partial l \partial k}\frac{\partial F}{\partial k \partial \gamma} + \frac{\partial F}{\partial k \partial k}\frac{\partial F}{\partial l \partial \gamma}\right] \end{aligned} \tag{19}$$

Because the determinate will always be positive by the definition of the second order condition, we can focus on the interior of the brackets. If positive (negative), then insurance will lower (raise) use of that input. To sign Equation 19, we need to determine the partial derivatives. All six partials are included in the appendix. All the partials help define the impact of insurance on multiple input use.

Fishers must be risk averse, and inputs must contribute to risk management in some way. Otherwise, there will be no impact on insurance.

Proposition 1.4. *Risk neutral fishers will not change their input use with index insurance*

Proof. Risk neutrality implies that $u'(k,l) = 0$ and $u''(k,l) = 0$. Subbing $u''(k,l) = 0$ into both Equation 28 and Equation 29 forces them to both equal zero. Plugging zero for $\frac{\partial F}{\partial l \partial \gamma}$ and $\frac{\partial F}{\partial k \partial \gamma}$ into Equation 19 makes both elements also zero in the interior. Thus risk neutral fishers would not change input allocation with the addition of index insurance.

□

To help prove the remaining propositions, the following corollary will be valuable.

Corollary 1.1. *Marginal profit in the bad state of the world is greater (less) than marginal profit in the good state for risk decreasing (increasing) inputs. If inputs have zero risk effects, the marginal profits are equivalent in both states.*

The proof is included in the appendix.

Proposition 1.5. *Index insurance will not change the input allocations when all inputs possess no risk effects.*

Proof. The second part of Corollary 2.1 states that the marginal profits across states are equal. If the marginal profits across states are equal, then in Equation 28 and Equation 29 the weight between positive and negative utilities is also equal and cancel out leading to Equation 28 and Equation 29 both equaling zero. Plugging zeros into Equation 19 for the insurance partials leads to an interior zero and no change in input use.

□

Risk averse fishers will buy actuarially fair insurance. If the inputs possess risk effects then they will lead to changes in the input. Proposition 1.6 defines the change in multiple inputs simultaneously with insurance.

Proposition 1.6. *With multiple inputs, index insurance will raise (lower) use of risk increasing (decreasing) inputs in accordance to an inputs individual risk effects when the following sufficient condition is true:*

$\frac{\partial F}{\partial k \partial l} > 0$ *when both inputs share the same risk effects, and* $\frac{\partial F}{\partial k \partial l} < 0$ *when inputs have opposite risk effects.*

Otherwise, Index Insurance will have ambiguous effects on each input allocation.

Proof. Corollary 2.1 allows us to sign Equation 28 and Equation 29 for any risk effect on either input. Concave utility by definition leads to $u'' < 0$. For simplicity, we'll only focus on Equation 28, but all applies equally to Equation 29. Insurance payouts equalize profits between different states. If insurance completely covers all loss, then we can rewrite equation Equation 28 as

$$\frac{\partial F}{\partial k \partial \gamma} = \overbrace{\overbrace{(1-p)pu''(\cdot)}^{-}\overbrace{[\frac{\partial \pi_b}{\partial k} - \frac{\partial \pi_g}{\partial k}]}^{-}}^{+} \tag{20}$$

Corollary 2.1 allows us to sign the interior brackets of Equation 20. Risk increasing (decreasing) inputs make the interior negative (positive). Thus, when an input is risk increasing (decreasing), we can sign Equation 28 and Equation 29 as positive (negative). Equation 24 and Equation 25 will always be negative due to concave utility.

Suppose both inputs are risk increasing so Equation 28 and Equation 29 are positive. The only way for Equation 19 to be unambiguously positive is for Equation 26 and Equation 27 to be positive.

$$\frac{\partial k}{\partial \gamma} = \overbrace{\frac{-1}{Det}}^{-} \left[\overbrace{\overbrace{\frac{\partial F}{\partial l \partial l}}^{-} \overbrace{\frac{\partial F}{\partial k \partial \gamma}}^{+} - \overbrace{\frac{\partial F}{\partial k \partial l}}^{-} \overbrace{\frac{\partial F}{\partial l \partial \gamma}}^{+}}^{-} \right] > 0$$

$$\frac{\partial l}{\partial \gamma} = \overbrace{\frac{-1}{Det}}^{-} \left[\overbrace{\overbrace{\frac{-\partial F}{\partial l \partial k}}^{-} \overbrace{\frac{\partial F}{\partial k \partial \gamma}}^{+} + \overbrace{\frac{\partial F}{\partial k \partial k}}^{-} \overbrace{\frac{\partial F}{\partial l \partial \gamma}}^{+}}^{-} \right] > 0$$

Both risk increasing inputs will be raised with index insurance. The results hold for risk decreasing inputs as the overall signs flip. Risk decreasing inputs will be lowered with index insurance.

Now suppose inputs have mixed risk effects. For simplicity, capital will be risk increasing and labor will be risk decreasing. The results will hold for the opposite case. By Corollary 2.1, Equation 28 is positive, while Equation 29 is negative. Equation 19 will be unambiguously positive if Equation 26 and Equation 27 are negative.

$$\frac{\partial k}{\partial \gamma} = \overbrace{\frac{-1}{Det}}^{-} \left[\overbrace{\overbrace{\frac{\partial F}{\partial l \partial l}}^{-} \overbrace{\frac{\partial F}{\partial k \partial \gamma}}^{+} - \overbrace{\frac{\partial F}{\partial k \partial l}}^{+} \overbrace{\frac{\partial F}{\partial l \partial \gamma}}^{-}}^{-} \right] > 0$$

$$\frac{\partial l}{\partial \gamma} = \overbrace{\frac{-1}{Det}}^{-} \left[\overbrace{\overbrace{\frac{-\partial F}{\partial l \partial k}}^{+} \overbrace{\frac{\partial F}{\partial k \partial \gamma}}^{+} + \overbrace{\frac{\partial F}{\partial k \partial k}}^{-} \overbrace{\frac{\partial F}{\partial l \partial \gamma}}^{-}}^{+} \right] < 0$$

The risk increasing input will be raised with index insurance, while the risk decreasing input will be lowered.

□

Proposition 1.6 shows that index insurance can have clear impacts even in complex settings with multiple inputs provided the sufficient condition holds. However, it is not clear ex-ante what the sign of the cross partial inputs of the first order condition should be. Equation 26 and Equation 27 themselves could be ambiguous. Rearranging Equation 26 and Equation 27 shows that the relative weight between the marginal profits of each input $\frac{\partial f}{\partial k}$ and the risk effects cross partial $\frac{\partial h}{\partial k \partial l}$ will determine the overall sign of the first order cross partials. Essentially, fishers change their inputs depending on whether a given input makes the other input more productive than the risk it adds. Dividing Equation 27 by $-\frac{u'}{u'}$ allows us to rearrange terms to show the tension between mean production and risk effects.

$$
\begin{aligned}
-\frac{\partial F}{\partial k \partial l} &= (1-p)u' \frac{-u''}{u'} \frac{\partial \pi_g}{\partial k} \frac{\partial \pi_g}{\partial l} - (1-p)u' \frac{\partial \pi_g}{\partial k \partial l} \frac{u'}{u'} \\
&+ pu' \frac{\partial \pi_b}{\partial k} \frac{\partial \pi_b}{\partial l} \frac{-u''}{u'} - pu' \frac{\partial \pi_b}{\partial k \partial l} \frac{u'}{u'} \\
&= (1-p)u' [\frac{-u''}{u'}] \frac{\partial \pi_g}{\partial k} \frac{\partial \pi_g}{\partial l} + pu' [\frac{-u''}{u'}] \frac{\partial \pi_b}{\partial k} \frac{\partial \pi_b}{\partial l} \\
&- (1-p)u' \frac{\partial \pi_g}{\partial k \partial l} - pu' \frac{\partial \pi_b}{\partial k \partial l}
\end{aligned} \tag{21}
$$

The concavity of profit with positive risk aversion $\frac{-u''}{u'}$ lead line 3 in Equation 21 to be positive. The cross partials in line 4 paint a more complicated picture. Whether inputs enhance or reduce the risk effect qualities of each other influences the weight of line 4. When inputs share risk effects, they ought to increase the risk effects of each other so that $\frac{\partial h}{\partial k \partial l} > 0$. Therefore line 4 in Equation 21 becomes more negative as all terms are positive. It is relatively more likely that Equation 21 is negative when risk effects are shared.

When risk effects are mixed, with one input increasing and one input decreasing, the risk effects counteract each other $\frac{\partial h}{\partial k \partial l} < 0$. Line 4 in Equation 21 becomes relatively less negative. If the difference between the risk effects cross partial $\frac{\partial h}{\partial k \partial l}$ outweigh the mean production cross partial $\frac{\partial f}{\partial k \partial l}$ then line 4 becomes unambiguously becomes positive. Then $-\frac{\partial F}{\partial k \partial l} > 0$ and $-\frac{\partial F}{\partial l \partial k} > 0$. The relative changes with complimentary or counteractive risk effects matches the signs needed for the condition in Proposition 1.6 to hold.

Despite the seemingly rigid conditions, Proposition 1.6 is quite powerful. It states that the direction all inputs should change is based solely on the characteristics of their own risk effects. Other inputs may influence the magnitude of change, but the direction is unequivocal. It remains unclear how much overall harvest will change. Simulations show the total impact on harvest can vary substantially, and that the conditions to ensure unambiguous change can be met. Though when applied with real world estimates of risk effects, the conditions may not hold and the effects of index insurance may not follow simple rules.

1.4. Numerical Simulations

We use a simple numerical simulation to test the necessary conditions in Proposition 1.6 and to determine the magnitude of change in input use for Norwegian fisheries using the parameters found in Asche et al., (2020). First, we present the simulations from the two input case to gain additional insight into how index insurance changes multiple inputs. Fisher earn profit through harvest with a Just and Pope production function with mean biomass normalized to one, and convex cost function.

$$
\pi(k,l) = \hat{B} k^{\alpha_k} l^{\alpha_l} + \omega k^{\beta_k} l^{\beta_l} - c_k k^2 - c_l l^2 \tag{22}
$$

Random shocks (ω) are distributed normally with a mean of zero and a standard deviation of σ_w. Capital (k) and labor (l) have both mean production elasticities (α_k and α_l) and flexible risk elasticities (β_k and β_l). Fishers choose both capital and labor to maximize expected utility. We use a constant absolute risk aversion utility function.

Multiple index insurance policies are tested through changes in coverage and trigger levels. One scenario set constant payout amounts at 50% of pre-insurance profit and the other allows fishers to choose payouts. Trigger levels are set to engage at any below average weather, shocks of more than 75% loss, and catastrophic shocks that reduce biomass below 90%. All premiums are actuarilly fair. We vary fisher production parameters and risk aversion to create a comprehensive dataset of possible combinations. Risk effects vary between -0.7 and 0.7 with iterative increases of 0.1 ignoring situations of 0 risk effects. Fishers can posses low, medium, and high mean elasticity values $\alpha \in \{0.25, 0.5, 0.75\}$. Coefficient of constant absolute risk aversion ranges from 1 to 3. Within each scenario, a Monte Carlo simulation creates 1000 weather random weather shocks with three variants of standard deviation $\sigma_w \in \{0.33, 0.66, 1\}$.

1.4.1. Numerical simulation results

Increasing insurance incentivizes fishers to use more risk decreasing inputs and less risk increasing inputs (Figure 2). The conditions of Proposition 1.6 can be satisfied with CARA utility, a Just-Pope Production function, and normal values of mean and risk elasticities. Index insurance also increases utility shown by the green lines in Figure 2, but there exists an optimal amount of insurance coverage for fishers. The optimal values of insurance are generally lower when fishers use risk decreasing inputs. The inputs and insurance act as substitutes for each other both lowering the variance of income fishers experience.

```
Warning: Using `size` aesthetic for lines was deprecated in ggplot2 3.4.0.
i Please use `linewidth` instead.
```

```
Warning: package 'patchwork' was built under R version 4.3.2
```

Figure 2 shows that conditions of Proposition 1.6 can be satisfied, but it does not show the conservation outcomes of index insurance. Fishers use the new allocation of inputs to change their overall harvest and thus impact on the biomass of fish stocks. Harvest changes are influenced by the relative combination of risk effects, mean production elastiticies, and the amount of insurance. Fishers reduce harvest more aggressively with risk decreasing inputs when offered a set contract of 50% coverage of pre-insurance profits (Panel A) relative to their optimal choice (Panel B) (Figure 3). Allowing fishers to choose their insurance coverage leads them to increase harvest more with risk increasing inputs. This phenomenon relates back to Figure 2. A 50% coverage is an overinvestment in insurance for risk decreasing inputs and an underinvestment for risk increasing inputs.

Mixed risk effects reduce the overall impact on harvest. The more flexible risk parameter dominates the less flexible one in terms of which input reduces overall harvest shown in the top left and bottom right quadrants of both panels in Figure 3.

```
Warning: package 'scales' was built under R version 4.3.2
```

Increasing the mean elasticities exacerbates the discrepancies between allowing fishers to choose insurance payouts versus receiving a set amount. When the productivity of harvest (α) is higher, the tradeoff between reducing variance and catch changes. Though insurance protects against risk, lowering the use of risk reducing inputs looses more mean catch with higher production elasticities. Fishers reduce aggregate harvest less with risk reducing inputs when mean elasticities are high. The opposite is true for risk increasing inputs. Insurance protects against the variance of adding more inputs and fishers receive a greater mean catch.

1.4.2. Application to Real World Fisheries

Asche et al., (2020) aggregated by vessel type and not species, so there is no reasonable estimate for biomass. They accounted for biomass using fixed effects in their regression, but without additional information, our simulations normalize biomass to 1 and only focus on the relative change in inputs and aggregate harvest. The simulation model extends the two input case to include fuel (f).

$$\pi(k,l) = k^{\alpha_k} l^{\alpha_l} f^{\alpha_f} + \omega k^{\beta_k} l^{\beta_l} - c_k k^2 - c_l l^2 - c_f f^2 \tag{23}$$

Table 1 shows the production and risk elasticities of the four vessel types used in the simulation. While not all elasticities were found to be statistically different from zero, we used their raw values because dropping only those variables that are significant in both matching parameters would have kept only a few valid combinations. All non-significant elasticities were led to small changes as expected, but we could continue to observe their interactions and changes in directions.

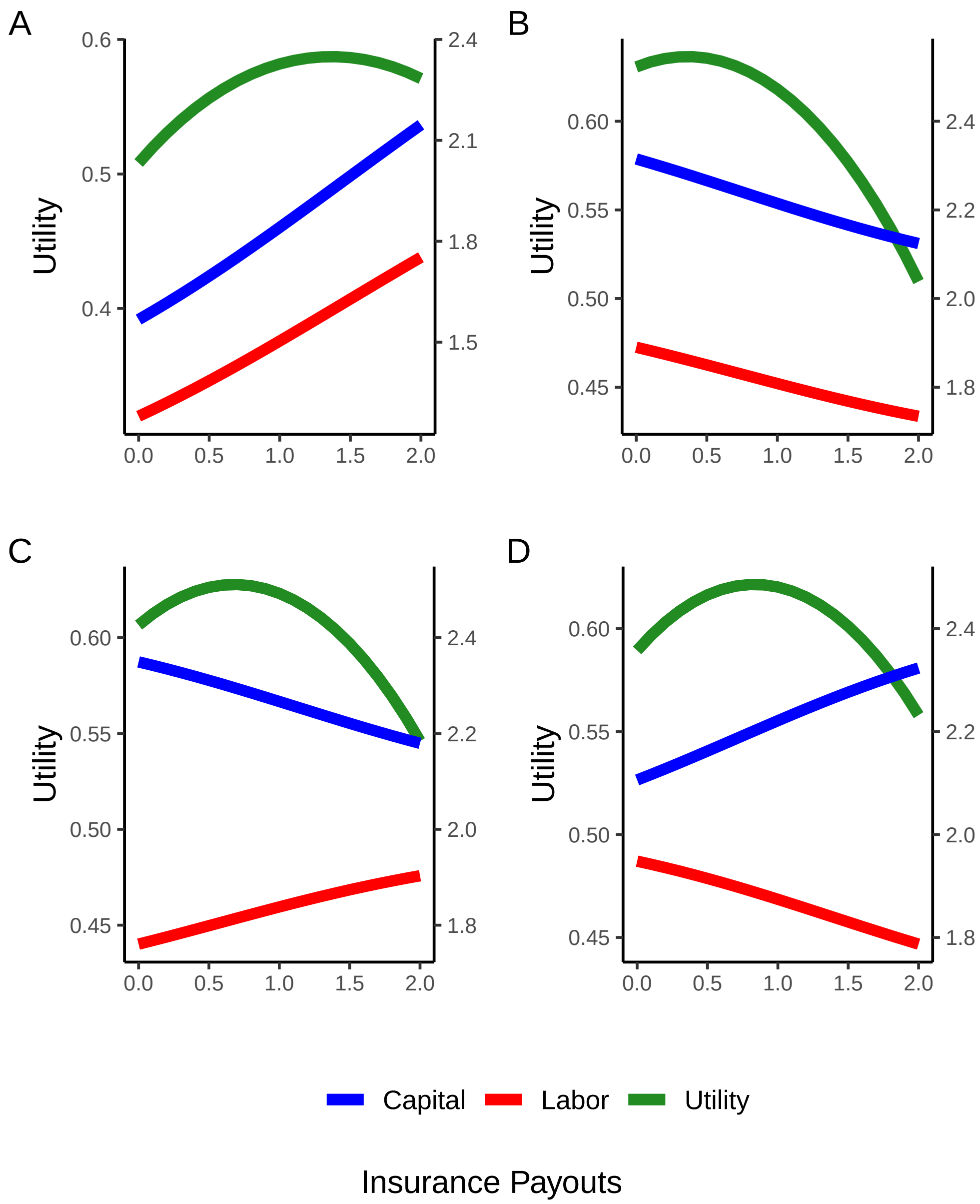

Figure 2: Fisher utility (green line) is concave in insurance payouts. Inputs change in accordance to their individual risk effects. The secondary y-axis shows input allocations for capital (blue line) and labor (red line). Panel A has both inputs with positive risk effects ($\beta = 0.5$). Panel B has both inputs with negative risk effects ($\beta = -0.5$). Panel C shows the effects when capital is a risk decreasing input ($\beta = -0.5$) while labor is risk increasing ($\beta = 0.5$). Panel D flips the risk effects of capital and labor.

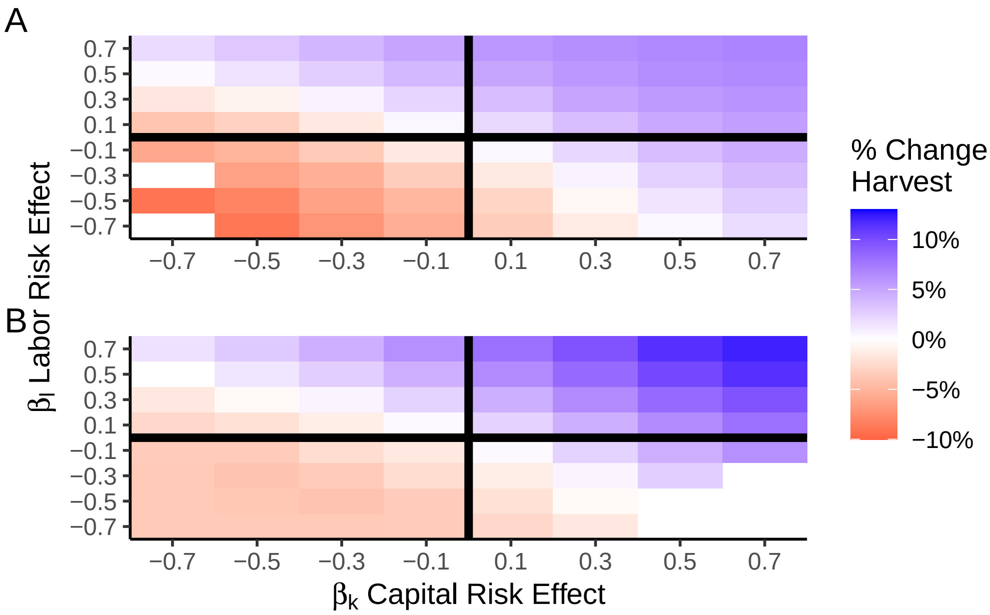

Figure 3: Percent Change in fishing harvest when fishers use index insurance with low mean elasticity values ($\alpha_{k,l} = 0.25$). In Panel A, Insurance payouts are a set variable. In Panel B, fishers choose insurance payouts. Red colors show overall decreases in harvest while blue colors show overall increases in harvest.

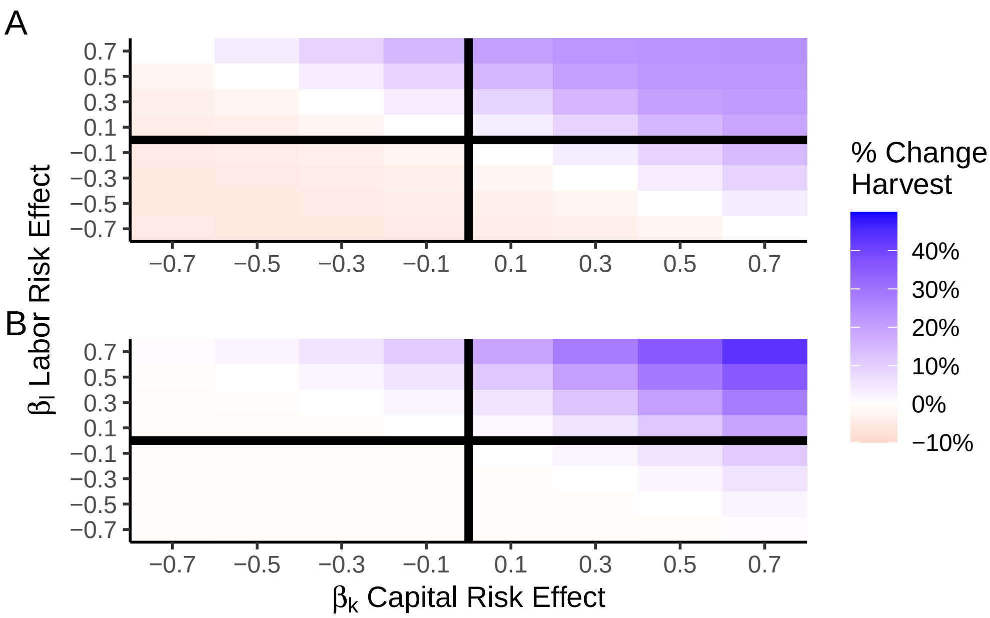

Figure 4: When fishers choose insurnace, they drastically increase (blue) harvest with risk increasing relative to no insurance harvest. Inputs share the same mean elasticity ($\alpha_{k,l} = 0.5$). Insurance payouts are a choice variable. Risk aversion is set to 1. Weather variance is 0.5

```r
load(here::here("data","asche_runs_5_13_al.RData"))

asche_runs_5_13_al |>
  select(method,ak,al,af,bk,bl,bf) %>%
  mutate(across(starts_with("alpha"),~round(.,2))) %>%
  mutate(across(starts_with("beta"),~round(.,2))) %>%
  mutate(method=case_when(method=="coast_sein"~"Coastal Seiners",
                          method=="coastal_ground"~"Coastal Groundfish",
                          method=="purse_sein"~"Purse Seiners",
                          method=="trawler"~"Groundfish Trawlers")) %>%
  knitr::kable(col.names=c("","$\\alpha_k$","$\\alpha_l$","$\\alpha_f$","$\\beta_k$","$\\beta_l$","
```

Table 1: Production and Risk elasticities of Norwegian Fisheries

	α_k	α_l	α_f	β_k	β_l	β_f
Coastal Seiners	0.294	0.421	0.457	0.184	-0.432	0.119
Coastal Groundfish	0.463	0.421	0.355	0.965	-0.080	0.113
Purse Seiners	0.941	-0.108	0.605	-0.454	-0.231	0.160
Groundfish Trawlers	0.210	0.106	0.531	-2.788	-0.110	-0.024

Index insurance in Norwegian fisheries would have lead to changes in input use and overall harvest. Table 2 shows that index insurance would have lead to a maximum change of 15% in total harvest for the coastal groundfish fishery. This was primarily driven by large increases in capital (20.36%) and fuel (8.89%). All inputs had relatively similar mean production elasticities, but capital was strongly risk increasing with the highest positive risk elasticity. Labor was a risk decreasing input, but also rose with insurance. This is an example where the conditions of Proposition 1.6 do not hold. The large discrepancy in production risk elastiticites is probably a reason for this in addition to the interactions terms at play by adding a third input. The chosen insurance payout was also much higher than the other vessel types. This reflects the observation from Figure 2 that that fishers choose higher levels of insurance coverage as a means to substitute the additional risk they are taking with expanded production.

Purse seiners saw the largest reduction in overall harvest. Capital for purse seiners is the most productive input out of all fisheries and inputs. Because it is risk reducing, it dominates the slightly risk increasing fuel input to lead the entire fishery to reduce harvest by 6.3%. this shows another violation of Proposition 1.6. In the opposite direction this time. Labor allocations did not change. No labor was allocated in either optimal choice, because the production elasticity was negative. Insurance payouts were also higher than the other fisheries that saw reductions. The high productivity of capital and fuel were most likely driving this result because small reductions in these productive inputs needed larger compensations.

Coastal seiners are perhaps the most intriguing outcome, because all parameters were significant and shows the conditions for Proposition 1.6 can hold in the real world with multiple inputs. All input use changes followed their respective risk effects. Capital (0.44%) and fuel (0.11%) both increased, while labor (-1.01%) decreased. In aggregate, there was a small reduction in harvest (0.3%). While insurance lead to a change, it was rather small and would not have a large impact on the fishery. The counteractive effects of the risk effects may negate some of the desire to change production as insurance incentivizes both in creases and decreases in harvest.

Inputs in the groundfish trawler industry were all risk reducing. Unsurprsingly, each input saw a reduction in use when index insurance was offered. Capital was exremely risk reducing and saw a 4.14% reduction in use, but was a relatively less productive input so overall harvest changed by only 1.4%. Inusrance payouts were selected to be low as seen in the two input simulations with risk decreasing inputs.

```r
asche_runs_5_13_al |>
  mutate(pct_f=(i_f-noi_f)/noi_f) |>
  select(method,pct_k,pct_l,pct_f,pct_h,gamma) %>%
  mutate(across(starts_with("pct_"),~scales::percent(.))) |>
  mutate(gamma=round(gamma,2)) |>
  mutate(method=case_when(method=="coast_sein"~"Coastal Seiners",
                          method=="coastal_ground"~"Coastal Groundfish",
                          method=="purse_sein"~"Purse Seiners",
                          method=="trawler"~"Groundfish Trawlers")) %>%
  knitr::kable(col.names=c("","Capital","Labor","Fuel","Harvest","Insurance Payout $\\gamma$"),esca
kableExtra::kable_classic()
```

```
Warning in kable_styling(kable_input, "none", htmltable_class = light_class, :
Please specify format in kable. kableExtra can customize either HTML or LaTeX
outputs. See https://haozhu233.github.io/kableExtra/ for details.
```

Table 2: Application of Index Insurance to risk effect parameters of Norwegian Fisheries

	Capital	Labor	Fuel	Harvest	Insurance Payout γ
Coastal Seiners	0.44%	-1.011%	0.11%	-0.3%	0.43
Coastal Groundfish	20.36%	6.578%	8.89%	15.4%	1.24
Purse Seiners	-4.39%	0.000%	-3.77%	-6.3%	0.81
Groundfish Trawlers	-4.14%	-0.979%	-0.69%	-1.4%	0.23

1.5. Discussion

Our paper is the first to investigate the interaction of risk effects and index insurance in a common pool resource. We emphasize a fishery setting due to burgeoning policy considerations and unique characteristics of fisheries that merit deeper elucidation. Index insurance has the potential to alleviate overfishing pressures in common pool fisheries. Risk effects control the direction and impact of index insurance on input use and harvest. Standard fishery models implicitly assume all inputs are risk increasing. Thus, applying index insurance in standard models will always demonstrate increases in fishing effort and reductions in stock biomass.

Risk decreasing effects need to be reconciled in a fisheries setting. Crop covers and pesticide provide clear examples in agriculture, but how do risk decreasing inputs exist in fisheries? Asche et al., (2020) provide empirical evidence of the existence of risk decreasing inputs, but do not elaborate on why or how labor and capital directly decrease risk. Labor is perhaps the more intuitive risk decreasing input. Technical expertise of crew and captains can hedge against luck when fishing[?] . Better trained crew can deploy gear in a safe and timely manner, increasing the likelihood of effective sets.

Capital is a more complex input, because it can be both risk increasing and decreasing. Capital investments in fisheries typically refer to vessel tonnage, engine power, and gear technology The spatiotemporal dimension of fishing decisions may explain how capital can potentially possess both risk effects. Fishers have to make decisions on where, when, and how long to fish that differ from the set grids of agriculture[?] . Capital offers protection from risk by allowing fishers to explore more fishing grounds, use more secure gear, and fish in more adverse weather conditions. When common pool resources incentivize the race to fish, having larger vessels may be a risk reducing input as the sooner a fisher can catch they assure their income at the expense of other fishers. Adding risk aversion to standard models of common pool fisheries suggests fishers should lower their capital use compared to risk neutral allocations[?] [?] . Yet, overcapitalization and overfishing are more often observed in the real world. Either fishers are never risk averse or the risk effects of capital are not as simple as the standard model suggests. When capital is allowed to be a risk decreasing, optimal allocations are much higher than risk neutral equilibrium suggesting fishers are making rational, risk averse decisions.

The transfer between inputs and insurance reflects the substitution between self-insurance and formal insurance[?] . If index insurance is designed to reduce fishing capacity, efforts must be made to ensure that it does not take away from the self resiliency of fishers. Labor appears to be consistently risk reducing and acts as a form of self insurance. If index insurance incentivizes captains to hire less crew, the stock of fish may be preserved, but less employment may reverberate throughout the community. Fishing is often a primary employment opportunity in coastal communities. Lowering employment options may lead to increased poverty or concentrated wealth. The resiliency of the community would be compromised rather than enhanced. The same idea applies to capital. If fishers are overinvesting in capital to hedge against some form of risk, policymakers need to be sure the insurance is replacing maladaptive self insurance behavior.

The primary form of self insurance in fisheries is management. To this point our analysis explicitly modeled scenarios without the existence of management. Most fisheries are managed in some form. The interaction between management and insurance may be complementary or substitutes. For example, well managed fisheries that have responsive harvest control rules may not need insurance. The management system is already providing the necessary risk protection. Insurance demand and uptake may be low in these fisheries. Insurance may also complement management to provide the financial relief that management cannot offer. Managers often focus on the biological health of the fishery that can run at odds with fishers desire to enhance their income. Insurance can act as the financial relief and allow managers to pursue more active strategies to protect fish stocks without political resistance from lowered quotas. The interaction between insurance and management requires further investigation especially with the the numerous management strategies that exist in fisheries.

Design and access of insurance must also consider equity. The current federal disaster relief program is inequitable with bias towards large industrial vessels[?] . Replacing the program with an equally inequitable program would be foolhardy. Current US Farm subsidies, including insurance premiums, are heavily skewed towards large agribusinesses[?] . Dimensions of access, procedural, representation, and distribution must all be built into the design of new fishery index insurance programs[?] . For example, small scale fishers may have income constraints that prevent them from buying the initial contract. Microfinance options connected to insurance have been used in agriculture to alleviate this burden to some success[?] . Additionally, we must insure that is not only the vessel owners who reap the benefits of insurance, and provide income to the deckhands and crew who may be laid off during closures.

Ultimately, if index insurance is to be used in fisheries, it must be designed with clear objectives and intentions. Index insurance can meet objectives of income stability and risk reduction. There has been an implicit assumption by practitioners that index insurance will always lead to improved sustainability. Without considering the behavior change of fishers when adopting insurance, the outcomes may not be as expected. Index insurance will correct risk reducing overcapacity in specific fisheries providing boosts to the long term sustainability and conservation of fisheries.

2. Appendix A

Partial Equations

$$\begin{aligned}\frac{\partial F}{\partial k \partial k} &= (1-p)u''(\pi_g - p\gamma)(\frac{\partial \pi_g}{\partial k})^2 + (1-p)u'(\pi_g - p\gamma)\frac{\partial^2 \pi_g}{\partial k \partial k} \\ &+ pu''(\pi_b + (1-p)\gamma)(\frac{\partial \pi_b}{\partial k})^2 + pu'(\pi_b + (1-p)\gamma)\frac{\partial^2 \pi_b}{\partial k \partial k}\end{aligned} \tag{24}$$

$$
\begin{aligned}
\frac{\partial F}{\partial l \partial l} &= (1-p)u''(\pi_g - p\gamma)(\frac{\partial \pi_g}{\partial l})^2 + (1-p)u'(\pi_g - p\gamma)\frac{\partial^2 \pi_g}{\partial l \partial l} \\
&\quad + pu''(\pi_b + (1-p)\gamma)(\frac{\partial \pi_b}{\partial l})^2 + pu'(\pi_b + (1-p)\gamma)\frac{\partial^2 \pi_b}{\partial l \partial l}
\end{aligned} \tag{25}
$$

$$
\begin{aligned}
\frac{\partial F}{\partial k \partial l} &= (1-p)u''(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial k}\frac{\partial \pi_g}{\partial l} + (1-p)u'(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial k \partial l} \\
&\quad + pu''(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial k}\frac{\partial \pi_b}{\partial l} + pu'(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial k \partial l}
\end{aligned} \tag{26}
$$

$$
\begin{aligned}
\frac{\partial F}{\partial l \partial k} &= (1-p)u''(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial l}\frac{\partial \pi_g}{\partial k} + (1-p)u'(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial l \partial k} \\
&\quad + pu''(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial l}\frac{\partial \pi_b}{\partial k} + pu'(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial l \partial k}
\end{aligned} \tag{27}
$$

$$
\frac{\partial F}{\partial k \partial \gamma} = (1-p)u''(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial k}(-p) + pu''(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial k}(1-p) \tag{28}
$$

$$
\frac{\partial F}{\partial l \partial \gamma} = (1-p)u''(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial l}(-p) + pu''(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial l}(1-p) \tag{29}
$$

Corollary 2.1. *Marginal profit in the bad state of the world is greater (less) than marginal profit in the good state for risk decreasing (increasing) inputs. If inputs have zero risk effects, the marginal profits are equivalent in both states.*

By the first order conditions, there exist optimal values k^* and l^* that must be chosen before the realization of the states of the world. Therefore $h(k^*, l^*)$, $f(k^*, l^*)$, and $c(k^*, l^*)$ are equal across states.

Marginal utility in both states of the world is controlled by risk effects and the sign of the random variable ω. Risk increasing inputs have $h'(k, l) > 0$ by definition. For either input k, l denoted by x this holds

$$
\begin{aligned}
\frac{\partial \pi_b}{\partial x} - \frac{\partial \pi_g}{\partial x} &= \omega_b h'_x(k, l) + \cancel{f'_x(k, l)} - \cancel{c'_x(k, l)} \\
&\quad - \omega_g h'_x(k, l) - \cancel{f'_x(k, l)} + \cancel{c'_x(k, l)} \\
&= \omega_b h'_x(k, l) - \omega_g h'_x(k, l)
\end{aligned} \tag{30}
$$

If an input is risk decreasing then $h'_x(k, l) < 0$ with $\omega_b < 0$ and $\omega_g > 0$. Then Equation 30 is positive and marginal profit in the bad state is greater than the marginal profit in the good state. Adding more of a risk reducing input reduces the negative impact in the bad state relative to the good state.

$$
\frac{\partial \pi_b}{\partial x} - \frac{\partial \pi_g}{\partial x} = \overbrace{\omega_b h'_x(k, l) - \omega_g h'_x(k, l)}^{+}
$$

Repeating the same thing for risk increasing inputs $h'_x(k, l) > 0$ shows that marginal profit in the bad state is less than marginal profit in the good state.

$$
\frac{\partial \pi_b}{\partial x} - \frac{\partial \pi_g}{\partial x} = \overbrace{\omega_b h'_x(k, l) - \omega_g h'_x(k, l)}^{-}
$$

If inputs have no risk effects then $h'(k, l) = 0$. Subbing into Equation 30 shows there is no difference in marginal profits with no risk effects.

References